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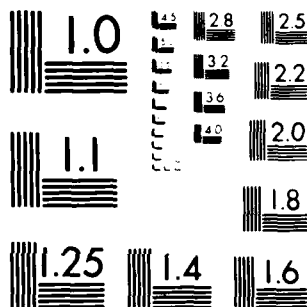UNCLASSIFIED   NPS-67-84-001   F/G 21/2   NL

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Monterey, California

THREE-DIMENSIONAL, PRIMITIVE-VARIABLE

MODEL FOR SOLID-FUEL RAMJET COMBUSTION

T. Milshtein and D. W. Netzer

February 1984

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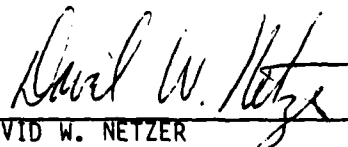
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A three-dimensional computer code has been developed for the solid-fuel ramjet combustion process. The code includes finite-rate chemical kinetics and has been used to predict the combustion behavior for axial inlet, side-dump inlet and bypass configurations.

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LIST OF FIGURES

NOMENCLATURE

A   -   constant in regression rate equation (7)

B   -   blowing parameter

C_p - specific heat at constant pressure

E   -   activation energy

h   -   enthalpy

h_f^0 - heat of formation

k   -   turbulence kinetic energy

$\dot{m}$ -   mass flow rate

$\bar{M}$ -   average molecular weight

m_i - mass fraction of species i

p,P - pressure

$\dot{q}''$ - heat transfer flux

r   -   radial distance

$\dot{r}$ -   fuel regression rate

R   -   universal gas constant

R_i - reaction rate of species i

T   -   temperature

u   -   axial velocity

v   -   radial velocity

w   -   tangential velocity

Γ_i - effective transport coefficient of species $i = \mu/\sigma_i$

δ -   incremental distance from wall

ϵ -   turbulence dissipation rate

μ -   effective viscosity

ρ -   density

σ_i - Prandtl or Schmidt number for species i

ϕ -   mixture fraction (mass fraction of total fuel)

subscripts

a   -   air

c   -   chamber

CO   -   carbon monoxide

CO_2 -   carbon dioxide

CH   -   intermediate hydrocarbon

f   -   solid fuel

fu   -   unburned fuel vapor

g   -   within the fuel grain

H_2 -   hydrogen

H_2O -   water

O_2 -   oxygen

p   -   near wall node point, port

T_w -   wall temperature

rad -   radiation

w   -   fuel wall

I. INTRODUCTION

The solid-fuel ramjet (SFRJ) most often consists of a solid-fuel grain which provides the walls for the combustion chamber. A sudden expansion at the air inlet (either axial or side-dump) can be used to provide flame stabilization. Downstream of the flow reattachment a turbulent boundary layer develops and includes a diffusion-controlled flame between the fuel-rich zone near the wall and the oxygen-rich central core. Due to that diffusion flame, heat is transferred by convection and radiation to the solid surface, causing vaporization of the fuel.

At the Naval Postgraduate School both mathematical modeling[1-4] and experimental efforts[5-10] have been conducted to determine the effects of design and operational variables on the obtainable performance.

The computer model simulation of the SFRJ combustion process has evolved from an original stream-function vorticity formulation[1] to a primitive-variable (pressure, velocity) model which includes an aft mixing chamber.[3] These axisymmetric models have not included radiative heat transfer to the fuel surface. This has limited the utility of the model, since many all-hydrocarbon fuels produce significant amounts of radiative transfer through the generation of carbon particulates in the flame zone. Recently[4], a simplified radiative model was included in the primitive-variable model and resulted in improved prediction of the fuel regression-rate profile. The primitive-variable codes were based on the Champion 2/E/FIX computer program developed by Pun and Spalding[11]. The Champion code is a two-dimensional code and therefore, could not be used to model two important SFRJ geometries; side-dump and bypass. The side-dump configuration has air injected through

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the side of the fuel grain and the dome region is constructed of fuel. The bypass configuration ducts a portion (typically 50%) of the total air flow into an aft mixing chamber. A full three-dimensional (3-D) model is needed to predict the flow-field in these configurations.

The side-dump configuration is a very difficult one to develop/optimize using only experimental data. There is a complex interaction between the location/size of the inlet dump, the length of the dome region upstream of the dump, and the resulting fuel regression rate pattern. Regression rate data for the side dump geometry have not appeared in the open literature. However, several general observations can be made. Swirling the inlet flow can increase and smooth-out the downstream fuel regression rate pattern. Regression rates within the dome region, upstream of the dump, can increase or decrease, depending upon the dome length, number of inlets and amount of swirl. 3-D models are, in this case, a necessity in the combustor development process.

Several 3-D, elliptic, primitive-variable codes have been developed. One such code, developed by the AiResearch Manufacturing Company,[12,13] is an extension of the Champion code. The former computer code was developed to model gas turbine combustors and formed the basis of the 3-D, SFRJ model discussed herein.

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II. MODEL OVERVIEW

The Garrett/AiResearch model is 3-D, elliptic, for steady, subsonic flow and includes finite-rate chemical kinetics. The dependent variables are u, v, w, h, k, ε, ϕ, m_{fu}, m_{CH}, m_{H_2} and m_{CO}. In addition, if radiation is included (a six-flux model), then three radiation flux vectors are calculated. Soot emissions can be calculated if desired. Liquid spray calculations can also be made but were not necessary in the SFRJ model. The turbulence model is the same as used in the Champion program, namely the modified two-equation (k-ε) model of Jones, Launder and Spalding[14-15].

Hydrocarbon combustion is considered to be a four-step process as follows:

$$C_x H_y \rightarrow C_x H_{y-2} + H_2 \tag{1}$$

$$C_x H_{y-2} + \frac{x}{2} O_2 \rightarrow xCO + \frac{y-2}{2} H_2 \tag{2}$$

$$CO + \frac{1}{2} O_2 \rightarrow CO_2 \tag{3}$$

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \tag{4}$$

Arrhenius rate expressions are used for each of the above reactions. These chemical kinetics limited rate expressions were compared to rate expressions based on an eddy-breakup model. The latter expressions attempt to account for the effects of turbulence intensity and scale and species concentration on the consumption rate of a particular reactant. The two-part boundary layer (divided by $y^+ = 11.5$) used in the Champion code is also employed. Details of the computer program, the differential equations and the line by line, finite difference solution procedure are presented in references 12 and 13.

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III. MODEL MODIFICATIONS AND SOLUTION PROCEDURES

The major modifications required of the Garrett/AiResearch model were geometric and the inclusion of a fuel wall on which finite-rate chemical kinetics could occur. The geometric changes required to model the SFRJ configurations were readily incorporated. Several additional variables and subroutines were necessary to include the regressing fuel surface effects. In addition, fuel property subroutines were changed to reflect the properties of Plexiglas (PMM) and HTPB, the two solid fuels used in the present study.

The governing equations on the boundary[16] for unity Lewis .be. are:

Energy:
$$\dot{q}_{rad}'' = (\rho v)_w (h_w - h_f) + \Gamma_{h_w} \left(\frac{\partial h}{\partial r}\right)_w \tag{5}$$
($\dot{q}_{rad}''$ can be calculated within the existing model ol was neglected in the present investigation.)

Species:
$$R_{i_w} = \Gamma_{i_w} \left(\frac{\partial m_i}{\partial r}\right)_w + (\rho v)_w (m_{i_w} - m_{i_g}) \tag{6}$$
(the values of R_i were calculated in the same manner as for the internal nodes)

It was assumed that the fuel regression rate could be represented in an Arrhenius format:[17]

$$\rho_f \dot{r} = (\rho v)_w = A \rho_f e^{-E/RT_w} \tag{7}$$

Using the Couette flow approximation for the boundary layer behavior with mass transfer[1,16]

$$\Gamma = \Gamma_{B=0} \frac{\ln(1+B)}{B} \tag{8}$$

where B can be evaluated from the enthalpy as

$$B = \frac{h_p - h_w}{h_w - h_{fg} - (\dot{q}_{rad}''/(\rho v)_w)} \tag{9}$$

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The enthalpy can be expressed as

$$h_w = \sum_i m_i (h_{f_i}^0 + \int_{T_{ref}}^{T_w} C_{p_i} dT) \qquad (10)$$

The solution procedure for the boundary conditions on the fuel wall was as follows:

(a) estimate T_w and B

(b) calculate $(\rho v)_w$ from (7)

(c) calculate Γ_{i_w} and Γ_{h_w} from (8)

(d) calculate m_{i_w} for all species from (6)

(e) calculate the other species $(m_{H_2O}, m_{OX}, m_{CO_2}, m_{N_2})$ from species conservation equations

(f) calculate h_w from (10)

(g) calculate B from (9) with $\dot{q}_{rad}'' = 0$
Iterate (c) to (g) until B converges

(h) calculate $(\rho v)_w$ from (5)

(i) calculate T_w from (7)
Iterate (b) to (h) until $(\rho v)_w$ converges

(j) calculate ρ_w from

$$\rho_w = \frac{p}{T \frac{R}{\bar{M}}}$$

(k) calculate v_w from $\frac{(\rho v)_w}{\rho_w}$

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It was found, as previously found by Netzer[1] and Stevenson and Netzer[3], that the near-wall turbulence dissipation had to be increased on the step face $(\epsilon_p = k_p^{3/2}/0.46)$ and that the grid spacing adjacent to the fuel surface had to be maintained slightly less than that required for $y_p^+ = 11.5$ in order to obtain temperature distributions in qualitative agreement with experimental data.

In order to obtain convergence it was necessary to input initial conditions which were in qualitative agreement with the final solution (for example, the fuel mass fraction had to be specified as decreasing from the wall) and under relaxation (typically 0.1 to 0.5) had to be used.

The accuracy of the solution for the entire combustor of the solid fuel ramjet is particularly sensitive to the boundary conditions on the fuel wall.

IV. RESULTS AND DISCUSSION

Four geometries were investigated (fig. 1); axisymmetric with axial inlet, bypass with axial upstream inlet , single side-dump and dual side-dump. All cases included an aft mixing chamber. For the axisymmetric, axial-inlet geometry the predicted reattachment "points" (where u near the wall was interpolated to zero) are shown in Fig. 2. The reattachment "points" were in good agreement with the maximum heat transfer locations measured by Krall and Sparrow[18] but shorter than those measured by Phaneuf and Netzer[6] in nonreacting flow with wall mass addition.

Normalized regression rate profiles are shown in Fig. 3. The experimentally measured profiles for PMM fuel were very sensitive to inlet turbulence/distortion. However, the 3-D code (with finite rate kinetics) predicted results very nearly identical to the mixing limited, 2-D code[3], i.e., the maximum regression rate was predicted to occur upstream of the experimentally measured point. The average regression rate was in good agreement with experiment.

Examples of typical radial profiles for u, m_{O_2}, m_{N_2}, and T near the grain exit are shown in Fig. 4. The effects of including finite-rate kinetics and/or the injection of O_2 that occurs into the boundary layer near the reattachmnt zone are readily apparent; a broad zone of high temperature near the maximum value and finite concentrations of oxygen below the flame.

Figure 5 shows regression rate profiles at three axial locations for the single side-dump geometry without inlet air swirl. Non-uniform, high

regression rates occur in the dump region. Lower regression rates in the dome region and more uniform regression rates near the grain exit are also observed.

Figure 6 shows the predicted regression rate results with two, 180° opposed side-dumps, with and without inlet air swirl. The effects of inlet swirl on this particular geometry are readily apparent. Inlet swirl decreased the regression rates in the dome, but significantly increased the rates downstream. Regression rate uniformity was also significantly improved except adjacent to the inlet dump.

Figure 7 shows the results of increasing the dome length and/or the inlet dump area. Increasing the inlet area resulted in increased fuel consumption in the dome region and increased nonuniformity downstream. Lengthening the dome above the reference value significantly reduced head-end fuel regression rates without major effects in the downstream regions.

V. CONCLUSIONS

The model predictions show that significant variatiions in fuel regression rate (both circumferentially and axially) are caused by the manner in which the air is injected into the fuel grain. In general, inlet swirl increases and smooths-out the fuel regression rate downstream of a side-dump inlet. The effects of inlet location and size on the regression rate behavior are difficult to estimate a-priori for a specific set of test conditions. The model must be used to predict the expected results. Much additional work is required in order to validate the predictions of the 3-D SFRJ model. However, the ability to examine the effects of inlet air location and flow characteristics on the fuel regression rate pattern (and the combustion efficiency, etc.) has provided a needed improvement to the earlier 2-D model.

Current work is being directed at incorporation of the soot production/consumption and radiation subroutines into the SFRJ configuration and combustion environment. Regression rate profiles for the more recent configurations are also being compared to experimental data as they become available.
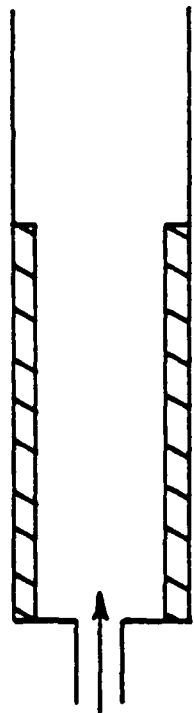
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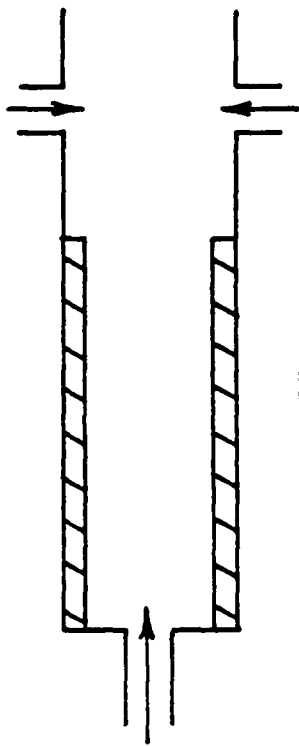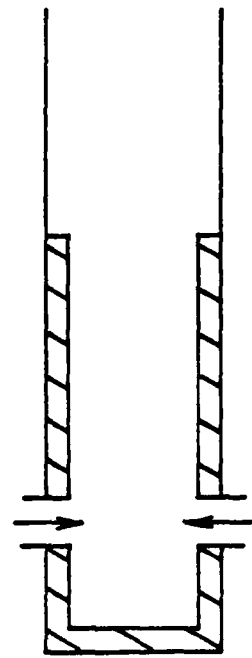
AXIAL INLET
WITH BYPASS
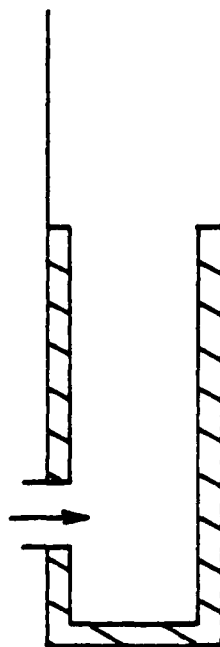
180° OPPOSED
SIDE-DUMP

AXIAL INLET

SINGLE SIDE-DUMP

Figure 1. Solid Fuel Ramjet Geometries in Model.

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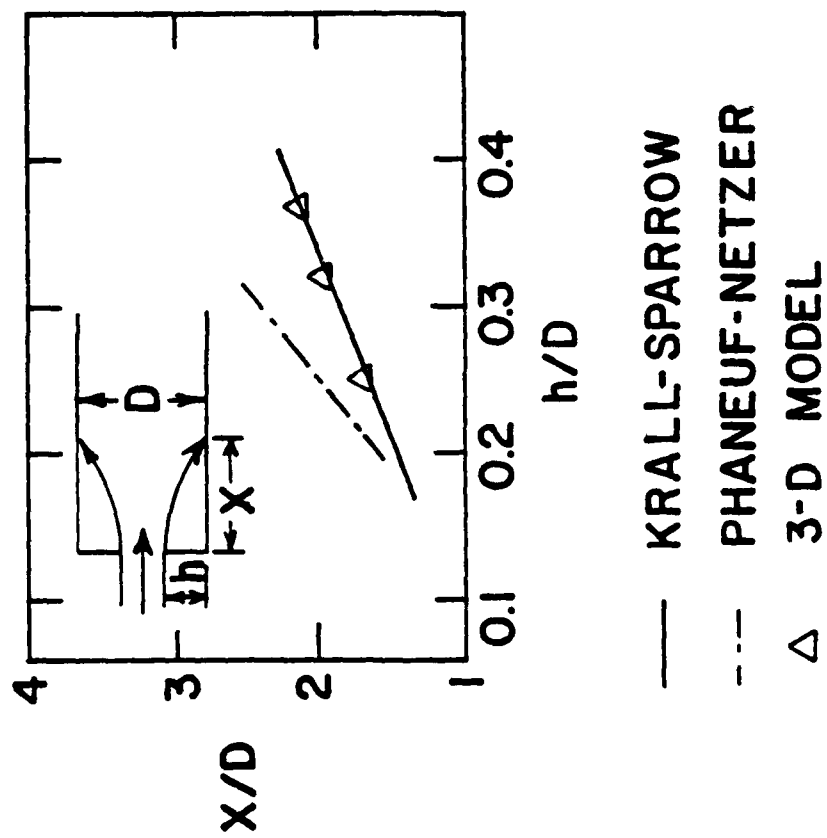
Figure 2. Reattachment Locations for Axial-Inlet Flow.

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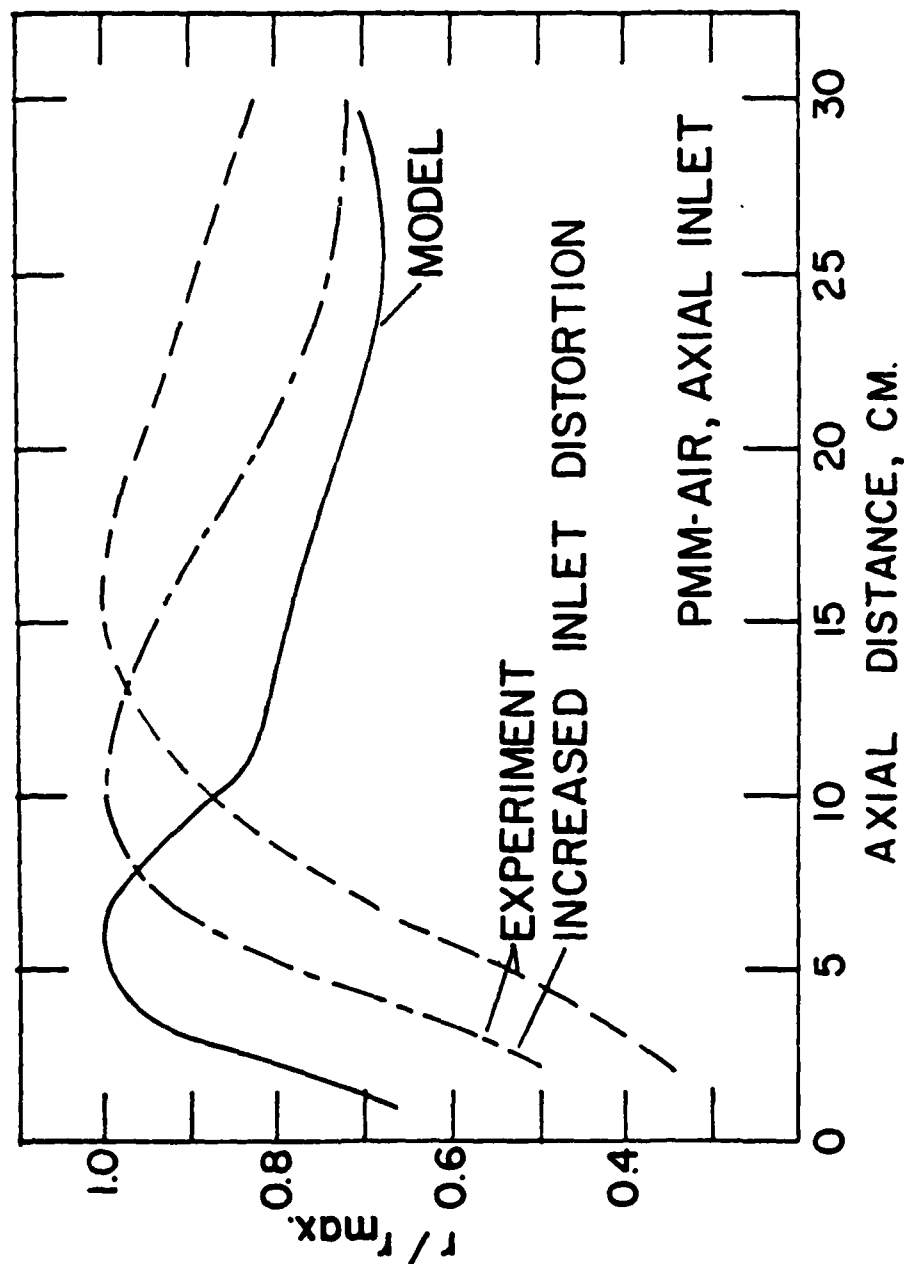
Figure 3. Fuel Regression Rate Profiles for Axial-Inlet Flow.
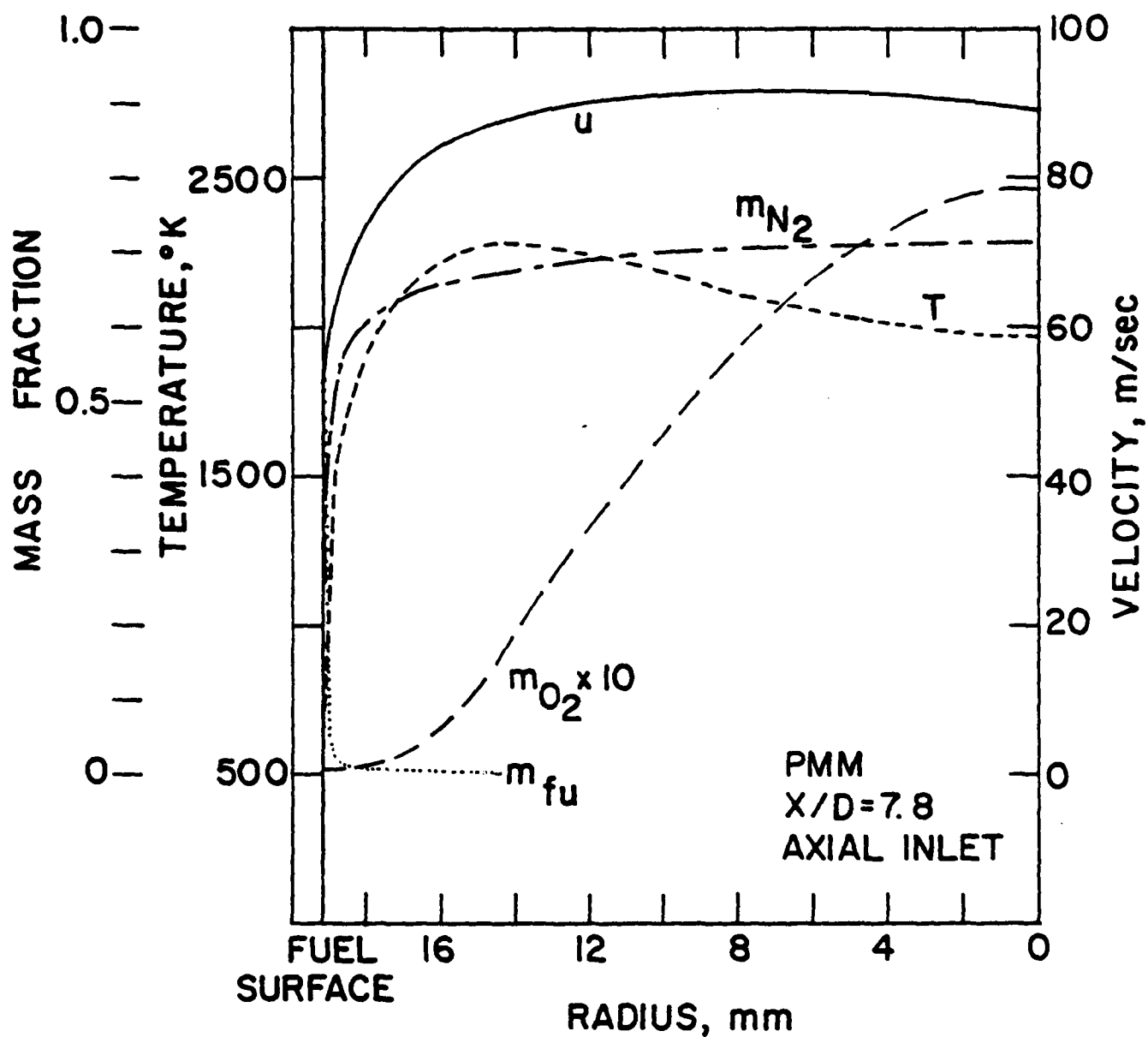
Figure 4. Predicted Radial Profiles for Gas Properties Near the Grain Exit, Axial-Inlet Flow.

PMM FUEL $\dot{m}_a$=0.07 kg/sec
D_p=0.038l m P_c= 4.76 atm.
INLET:97.5° x 0.0l2 m
NO SWIRL

1.0×10^{-4} m/sec
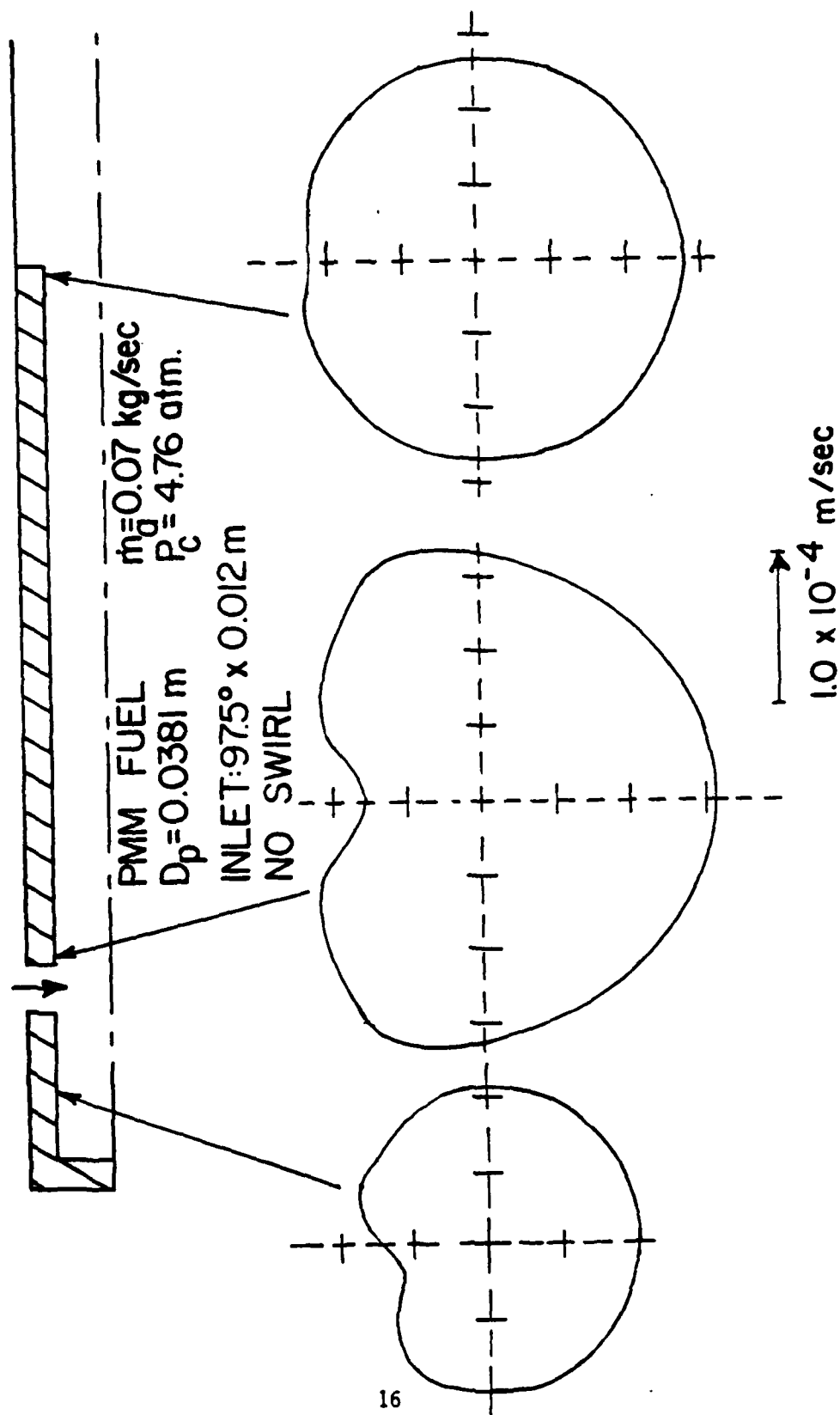
Figure 5. Fuel Regression-Rate Profiles, Single-Side Dump, No Inlet Swirl.

PMM FUEL
$D_p = 0.0381$ m
INLETS: 67.5° x 0.012m
$\dot{m}_a = 0.07$ kg/sec
$P_c = 4.76$ atm.

1.0×10^{-4} m/sec

— — — NO SWIRL

———— 30° θ and
AXIAL SWIRL
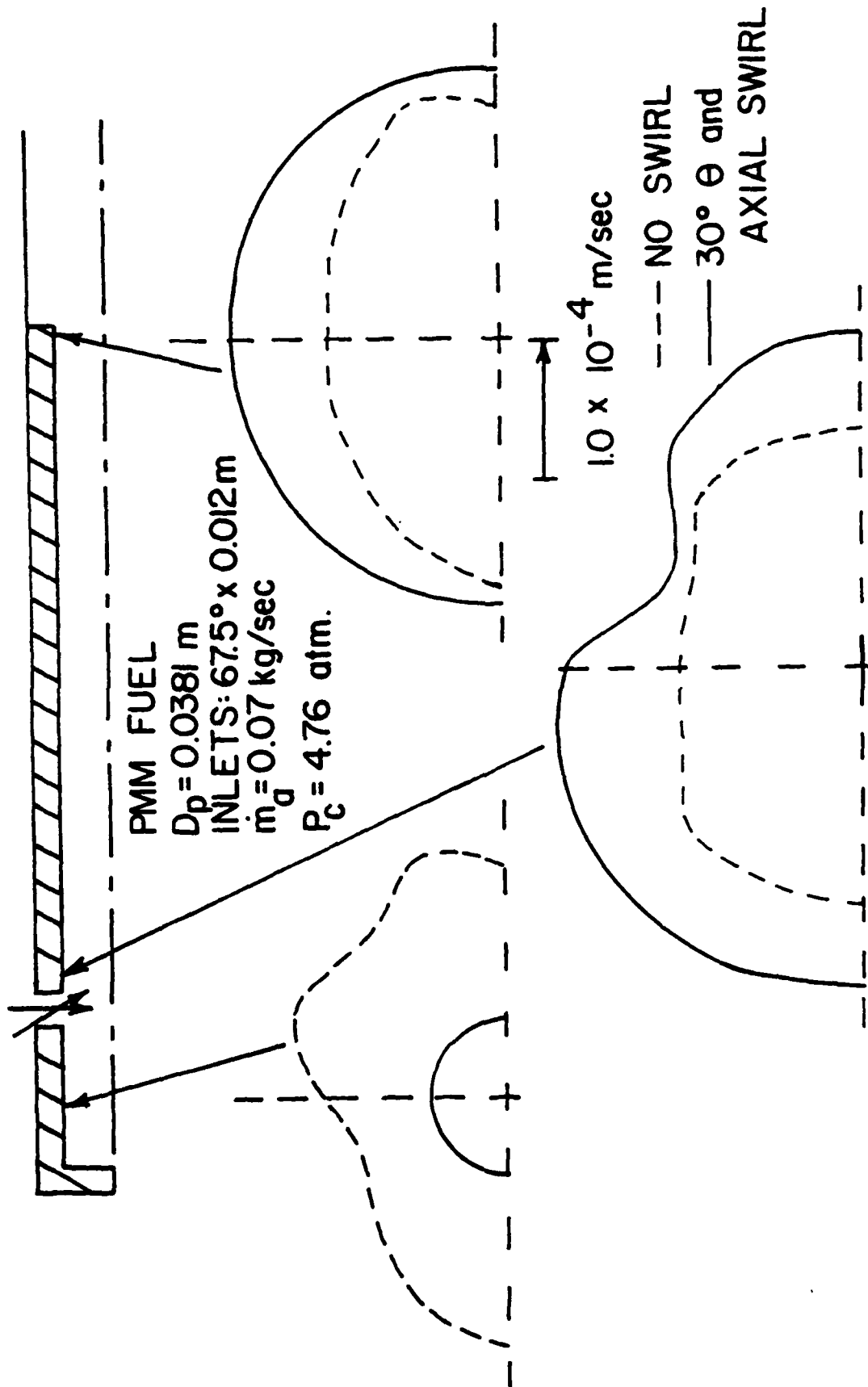
Figure 6. Effects of Inlet Swirl on Fuel Regression Rate Profiles, 180° Opposed
Side-Dumps.

PMM FUEL
$D_p = 0.0381$ m
INLETS: $67.5° \times 0.012$ m
or 0.0225 m
$\dot{m}_a = 0.07$ kg/sec.
$P_c = 4.76$ atm.
$30° \theta$ and
AXIAL SWIRL

1.0×10^{-4} m/sec
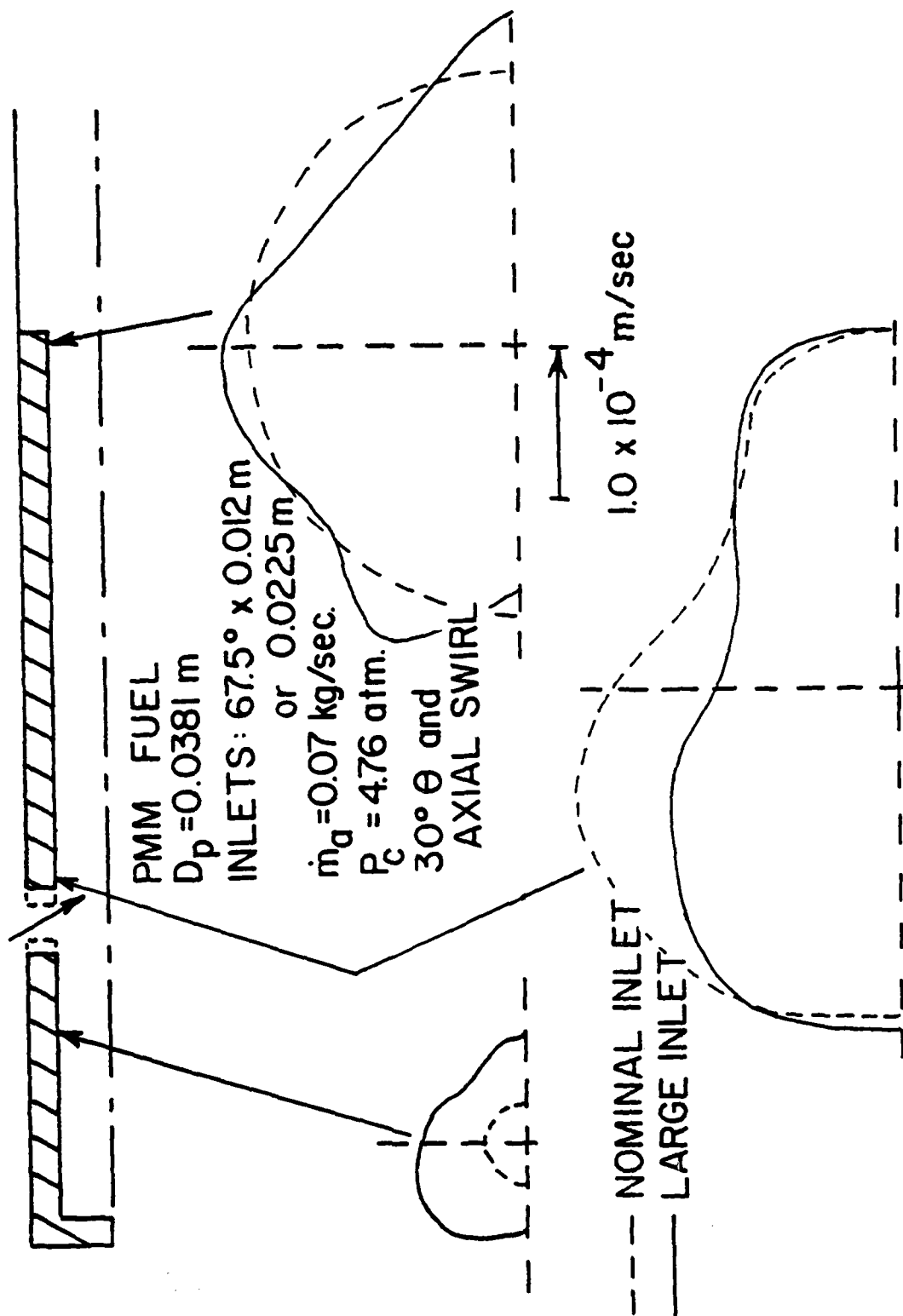
--- NOMINAL INLET
— LARGE INLET

Figure 7. Effect of Inlet Area and Dome Length on Fuel Regression Rate Profiles, 180°
Opposed Side-Dumps with Inlet Swirl.

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